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Review of LTCC Technology for Millimeter Waves and Photonics

Markku Lahti, Kari Kautio, Mikko Karppinen, Kimmo Keränen, Jyrki Ollila, and Pentti Karioja

Abstract—VTT Technical Research Centre of Finland Ltd. has developed and utilized Low Temperature Co-fired Ceramic (LTCC) technology for about 25 years. This paper presents our activities related to photonics and millimetre-waves, including also a relevant literature survey. First a short summary of the technology is given. Especially, the unique features of LTCC technology are described in more details. In addition, several examples have been given to show the validity of LTCC technology in these high-performance fields.

Keywords—LTCC, millimeter waves, photonics, assembly

I. INTRODUCTION

THE exploitation of the millimeter-wave (mm-wave) spectrum is essential to tackle the rapid growth of mobile data traffic and to enhance high-speed communication links due to inherently broad bandwidth enabled by mm-waves. Short-range applications such as near-field communications and wireless personal area networks are good examples where millimeter and sub-millimeter waves could be employed [1,2]. Millimeter-wave communication systems are currently being developed, for example, at 28, 38, and 60 GHz and E-band (71–76 and 81–86 GHz) for both 5G access and backhaul systems [3]. Anti-collision radar systems are also developed around 77 GHz [4]. Especially the unlicensed 57–66 GHz band is particularly suited for high-throughput short-range communications, e.g. for access points in small cells (radius of less than 50 m) with a high density of users [5]. Antennas with reconfigurable radiated beams are used to cover the wide angular sectors required in the applications.

Data transfer can also be done optically using optical fibre, planar optical waveguide or free space as media [6]. This requires the development of photonic packaging and integration; including lasers, photo detectors, micro-optical elements, optical fibers, laser drivers and photo detector amplifiers. Hybrid integration is the way to realize photonic systems in such a way that these basic elements are integrated onto a common substrate. The parts of the system must be fabricated by the use of cost-efficient, reproducible, well-established, high-volume manufacturing techniques. In photonic packaging, reliability and alignment tolerances are key issues. Therefore, system in a package concept (SiP) would be the most favorable approach in order to fulfill the requirements of photonic packaging.

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There is an increasing need to combine both photonics and electronic parts. At least the following aspects need to be considered:

- Devices alignment with μm or sub- μm -accuracy.
- Integration of high-speed/low-noise/high-power electronics as close as possible to the critical photonic devices.
- Matching of the thermal expansion coefficients between the devices and substrate.
- Providing required internal and external optical, electrical and mechanical interconnects as efficiently as possible.
- Providing required thermal management for critical power devices, such as, high-power lasers, laser drivers and amplifiers.
- Protecting devices against environmental conditions during the use and storage of the modules.
- Providing local hermetic sealing of critical devices, such as, diode lasers.

Of course, these requirements must be fulfilled by the most cost-efficient means in high-volume production with good production yield and reliability.

Our aim was to develop methods and technologies for packaging and integration based on the use of Low Temperature Co-fired Ceramic (LTCC) technology. This paper describes the capabilities of LTCC technology using some photonic and high-frequency modules as illustrating examples.

II. LTCC TECHNOLOGY

A. Overview

Low Temperature Co-fired Ceramic (LTCC) is a multi-layer glass ceramic substrate, sometimes referred to as "Glass Ceramics", because its main composition typically consists of glass and alumina as a filler. LTCC have advantages compared to other packaging technologies such as High Temperature Co-fired Ceramic (HTCC): the ceramic is generally fired below 1000 °C due to special composition of the material. This permits the co-firing with highly conductive materials (silver, copper and gold) instead of more resistive refractory metals (tungsten and molybdenum) used in HTCC processing. LTCC also features the ability to embed passive elements, such as resistors, capacitors and inductors into the ceramic package, minimising the size of the completed module although their tolerances are typically high. Other advantages of LTCC include mechanical rigidity and hermeticity, both of which being very important in high-reliability and environmentally stressful applications.

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The flow chart of the LTCC process is shown in Fig. 1. Each layer is processed individually. The process starts by making electrical and thermal via holes into individual tape sheets. The most common way to make these holes is using the mechanical punching method. Via holes are filled with conductor paste (Ag or Au) by stencil-printing, and solvents of the paste are removed by drying in an oven. The conductor layers are then screen-printed onto tape sheets and the paste solvent is again dried. The openings for cavities are punched at this stage. The layers are then stacked over each other and aligned by utilising the registration holes in the tapes. The stacked sheets are laminated in an isostatic chamber. Before lamination, the cavities are filled in by silicone inserts, which restrict the distortion of the cavities due to high lamination pressure. Co-firing is typically carried out at temperatures of 850-900 °C. The size of the fired panel varies from LTCC supplier to another. For example, VTT has the final panel size of ~100x100 mm². The panel contains several circuits, which can be separated by dicing.

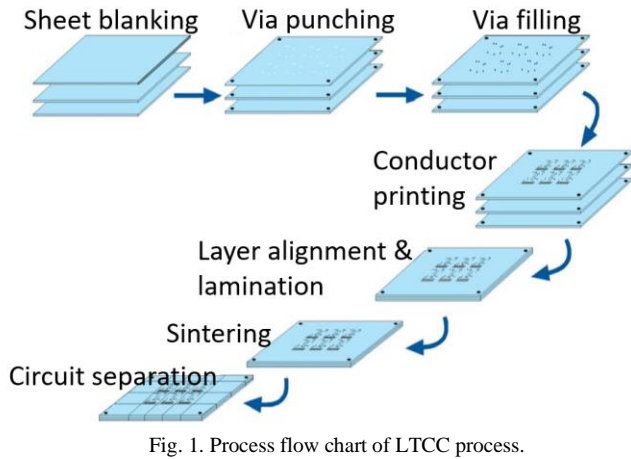


Fig. 1. Process flow chart of LTCC process.

B. Realization of conductors

The most important single processing step is the manufacturing of conductors. The most commonly used method is screen-printing. The practical linewidth limitation is around 40-50 µm [7]. Narrower lines require other methods, such as thin-film processing. The combination of sputtering/plating/etching has shown that lines down to about 15 µm are possible to achieve [8]. Thin-film processes are limited to the surface layers and of course they increase the costs.

C. Materials

Currently there are practically only two commercially available materials that are suitable for millimetre waves, namely Ferro A6-M and DuPont 9K7. Some companies are developing their own materials for their own use. The dielectric properties (loss tangent and dielectric constant) are generally functions of frequency. However, the properties remain quite constant up to 100 GHz as shown in Fig. 2 for A6M-E tape [9]. The characterisation of materials also show that the dielectric losses start to increase beyond about 0.3 THz as shown in Fig. 3 [10].

Probably the main concern in LTCC materials from manufacturing point of view is the sintering shrinkage variation.

This may affect the yield and complicate the assembly processes. A material system, which does not shrink in horizontal level at all, was developed and demonstrated up to Ka-band [11].

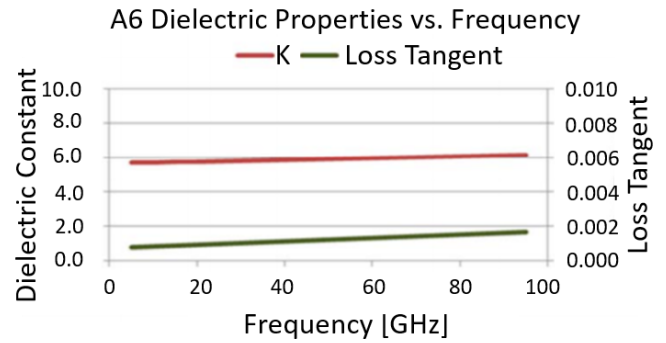


Fig. 2. Dielectric constant and loss tangent values for A6M-E tape system [9].

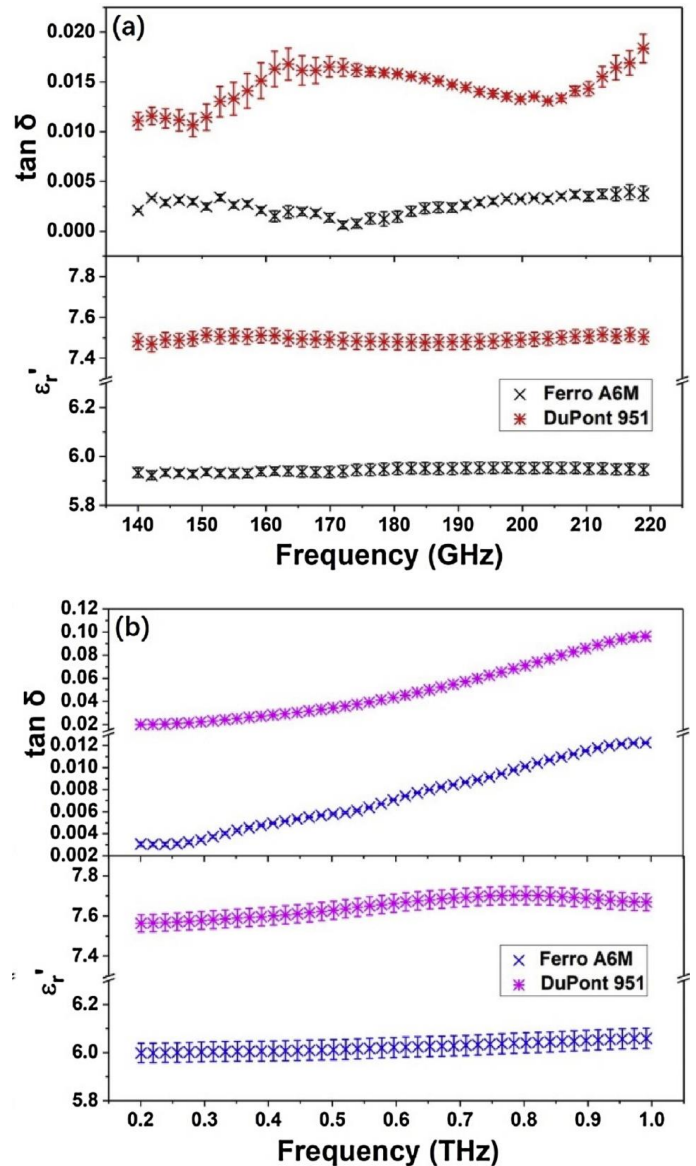


Fig. 3. Dielectric constant and loss tangent values for A6M-E and DuPont 951 tape system for higher mm-waves (a) and terahertz (b) [10].

It is also possible to restrict shrinkage by using so-called pressure assisted constrained sintering or pressureless constrained sintering [12]. In these processes, a release tape is laminated on both sides of the laminate to constrain the shrinkage during sintering. After sintering the release tapes have to be removed e.g. by mechanically brushing. This affects the quality of the co-fired conductors and complicates the processing. For example, a special batch furnace is required since in pressure-assisted sintering a force has to be applied to the laminate. In addition, post-sinter prints or plating processes are most likely needed to keep the conductor pads solderable and bondable.

D. Design

The lack of component libraries has been a bottleneck in the wider adaptation of LTCC technology. As early as in 2002, National Electronics Manufacturing Initiative (NEMI) announced in their roadmap the design infrastructure to be a major obstacle. Since then major design tool suppliers have included LTCC in their design data. Design libraries contain data for e.g. embedded passive components. However, as the frequencies increase, the structures are becoming more dependent on the material properties and application. The utilisation of libraries will become more complicated in those cases.

Generally speaking, LTCC design has to consider elements of both semiconductor and PWB design. Semiconductor design processes generally become highly standardized based on the minimum feature size attainable by a given process. This results in well-developed process design tools that closely integrate complex EDA design tools and fabrication processes. On the other hand, in the design of PWBs complex EM simulations are not typically needed, of course depending on the frequency range. Most designs can be done using calculations based on 50 ohm printed structures. Design of complex LTCC multilayer circuits requires designers to be flexible in their choice of structures (like that of a PWB designer) but must take into account high levels of complexity (like semiconductor designer).

E. Precision structures

For photonics, sensor and antenna applications, the ability to create 3D precision structures on the LTCC substrate is a very important feature. Open cavities can be made on the surfaces of the LTCC substrate in order to be able to assemble discrete semiconductor devices into the cavities. The assembly of active devices into the cavities allows for hermetic sealing of devices locally. U-grooves can be processed using punching and photolithographic processes on the substrate [13]. The groove structure provides precise alignment and firm attachment for the adhesive bonded optical fiber. Buried cavities or channels can be fabricated for liquid or gas flow to provide cooling or perform sample analysis, see Fig. 4. These structures can also be utilized under the patch antennas to reduce the effective permittivity.

Another method to enable precise alignment of devices is using through holes. The most accurate through hole structure is made by punching the hole to a single layer structure. On a multi-layer structure the hole can be punched through several layers after laminating the tape layers together, thus eliminating the layer-to-layer misalignment. The diameter of a through hole

can be controlled to $\pm 3 \mu\text{m}$ tolerance for the hole diameter range of 0.1 - 0.3 mm. The minimum hole pitch is typically 2 times the diameter of the hole.

These grooves, cavities, and through-holes processed in a standard LTCC process can be used for the passive alignment of optical fiber and diode laser [14]. The accuracy and the dimensional tolerances of such a groove depend mainly on the lamination parameters and the consistency of the lamination process. In addition, highly accurate punching process and small firing shrinkage tolerances are essential to be able to achieve the passive alignment accuracy of less than $10 \mu\text{m}$ that is acceptable for multimode fiber systems.

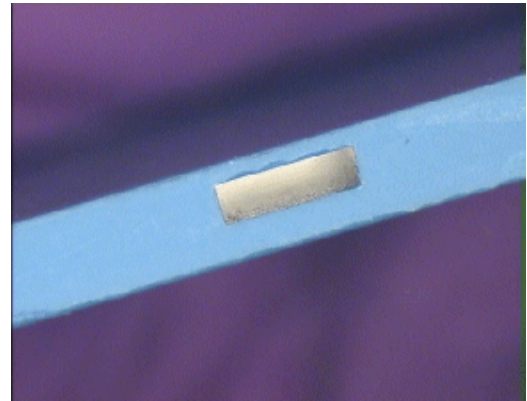


Fig. 4. Integrated embedded channel having the cross-section of $1.4 \times 0.4 \text{ mm}^2$ [13].

The feasibility of the laser-to-fiber passive alignment, schematically shown in Fig. 5, was verified by attaching a 200/220 μm multimode fiber with UV-curable adhesive onto a groove having a 10-mm length. The horizontal laser-to-fiber alignment accuracy was characterized by measuring the distance variation of via fiducials on both sides of the fiber groove, see Fig. 5. The fiducials can be used by the die bonder visual alignment system to align and center the laser accurately. Measurements carried out for several samples and substrates indicate that the die bonder alignment system can track the fiber groove with the accuracy of less than $3 \mu\text{m}$ and in most cases less than $2 \mu\text{m}$. The height measurements showed that the height of the fiber assembled onto the U-groove can be controlled with the accuracy of a few micrometers.

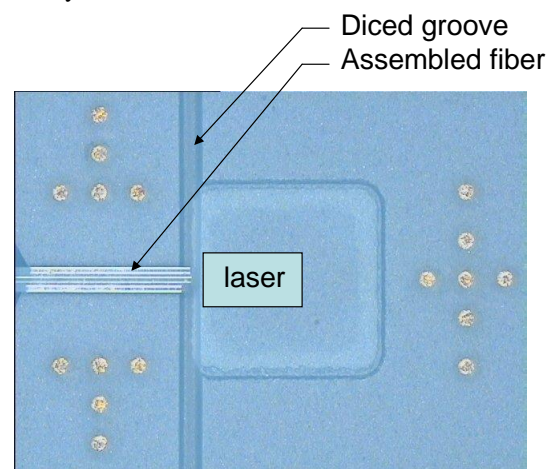


Fig. 5. A 200/220 μm multimode fiber attached onto the fiber groove ending to a cavity for a diode laser chip [14].

The use of through holes for photonic device is shown in Fig. 6 in which a photo detector array is aligned with the holes in the LTCC substrate [15]. The flip chip bonding of the array device on the other side of the substrate against the holes was made by the use of a precision flip chip bonder. The positioning accuracy of the bonder ($\pm 0.5 \mu\text{m}$) defined the final alignment accuracy of photonic devices. In addition, when the active devices are aligned by the use of the hole, the holes in the substrate can be used for the passive alignment and attachment of an optical fiber.

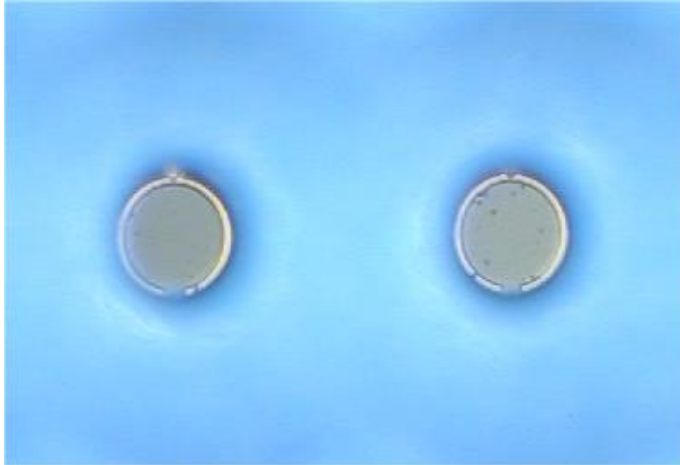


Fig. 6. Photo detectors with a $70 \mu\text{m}$ active area flip-chip-bonded on the backside of a LTCC substrate. The devices are aligned with the $80 \mu\text{m}$ diameter holes in the LTCC substrate [15].

F. Thermal management

Thermal conductivity of LTCC materials is better than that of organic substrates; in addition, heat spreaders and thermal vias can be fabricated during the normal processing phases of LTCC to further improve its thermal management capability. When using organic materials, heat spreading structures must always be used with high-power devices.

As mentioned earlier, embedded cavities can be used for liquid cooling. A more preferred method is to utilize thermal vias under the high-dissipative dies [16]. This is a natural way to realize thermal management structures since vias are needed anyway for electrical functions.

G. Encapsulation

Silicon does not provide cost-efficient means for mechanical protection and hermetic sealing. Of course, when using wafer scale packaging technologies, Si wafers can be bonded hermetically together but this does not solve the problem how to protect the circuits mechanically. Organic materials are not hermetic at all; semi-hermetic encapsulation can be obtained by the use of glob top materials. LTCC substrate is inherently hermetic, thus providing cost efficient and robust means for the sealing of active and passive devices hermetically.

III. EXAMPLES FOR MILLIMETRE WAVES

The technology has been studied for a variety of frequency ranges, including e.g. 24, 60 and 77 GHz applications. For example, a commercial product has been fabricated for 24 GHz radar applications [17]. The research work for radars has been continued up to 77 GHz. One example is shown in [18]. A

miniature radar front-end is shown in Fig. 7. The special feature in this case was the use of non-shrinkage LTCC materials. Most LTCC materials shrink during firing, however. The control of shrinkage is essential since it affects e.g. the flip-chip assembly process and also on electrical parameters.

Antennas are a popular research target since they are important parts of the most of modules. The reference [19] gives a comprehensive overview of the development of patch- and end-fire types antennas at VTT during last decade. Several different configurations for patch antennas have been studied. In addition to patch antennas, horn antenna types are becoming more and more important. Some examples are shown in [20,21]. Horn antennas can be realized by utilizing the possibility to realise vertical walls by vias. Two different configurations can be utilized. The inner side of the horn antenna can consist of ceramic, which is easier from the manufacturing point of view. Figure 8 gives an example of that. On the other hand, by using air inside the horn, higher frequency range can be realised. The structure in Fig. 9 has been used for even up to D-band (110-170 GHz).

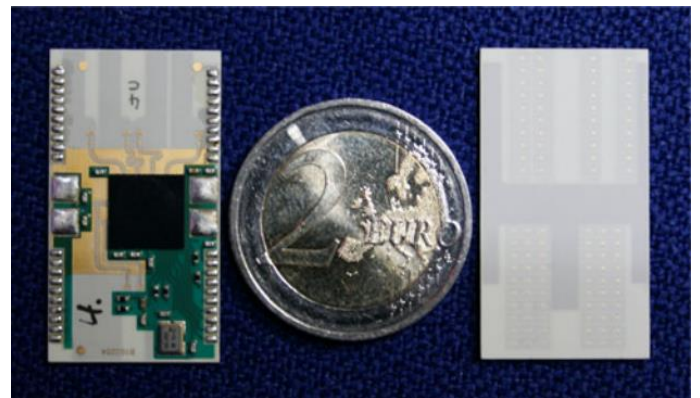


Fig. 7. Device and antenna side of miniature LTCC front-end radar [18].

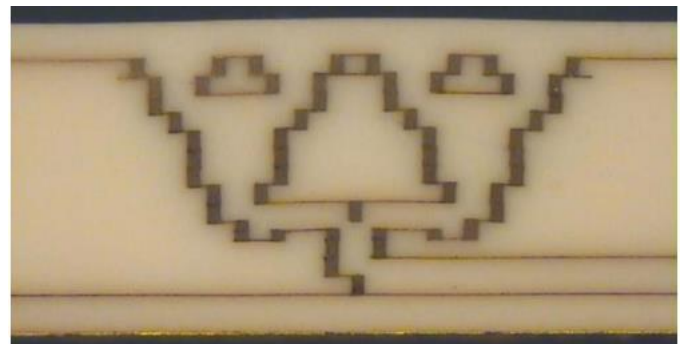
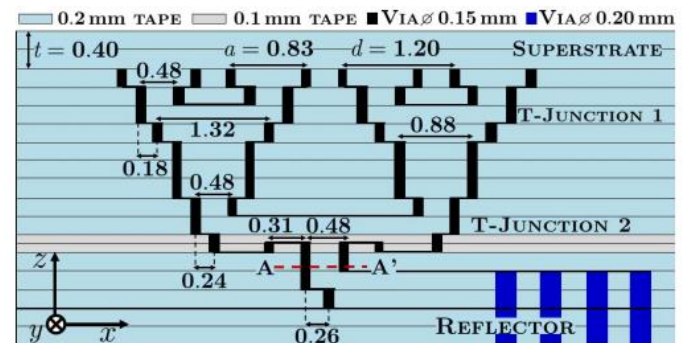


Fig. 8. Cross-section and photograph of dielectric-embedded parallel-plate waveguide feed network for 50-66 GHz band antenna [21].

Due to its good high-performance properties in harsh environments, LTCC technology is a good candidate for defence and aerospace applications. Publicly available information is scarce but at least one manufacturer reveals using LTCC for defence applications up to 44 GHz [22]. In addition, one manufacturer has carried out space-qualified program for their LTCC process [23].

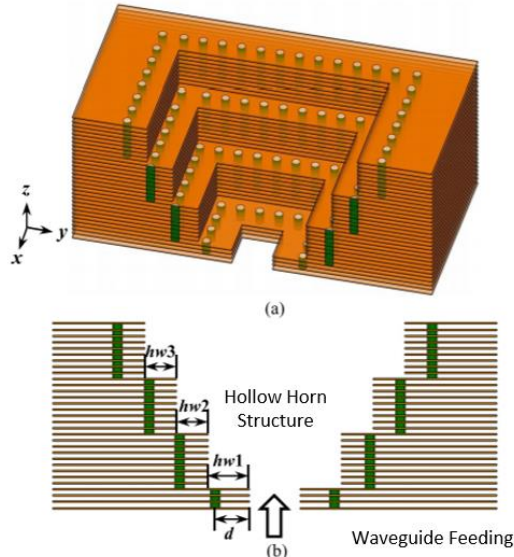


Fig. 9. Configuration of D-band horn antenna [23].

Substrate integrated waveguides could be potential solutions to avoid conductive losses of coplanar waveguides or microstrips. It is not practical to realise solid vertical walls in LTCC technology. Instead, walls are generally realised using via fence structures (just is also the case in PWB process). It has been shown that the method is feasible even up to 140 GHz [24]. The structures were based on 100 μm vias with 250 μm pitch which corresponds to typical LTCC design rules [25]. As the operating frequencies increase, the pitch of vias should become smaller to avoid the leakage of the signals. Usually, a good rule of thumb for the pitch is 1/10 of the wavelength.

The number of articles beyond D-band is obviously small. However, some work on LTCC antennas around 300 GHz has been published. In one of those, a receiver module for 300 GHz wireless communications, combining both photonics and wireless contributions, have been shown in [26]. The module consisted of LTCC substrates with integrated silicon-based lens antenna and flip-chip-bonded receiver chip as shown in Fig. 10.

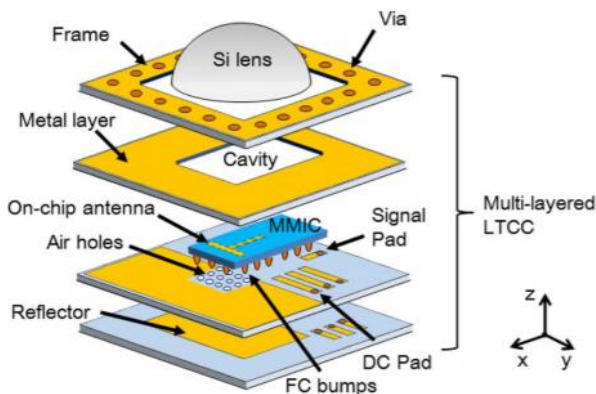


Fig. 10. LTCC multi-layered package for MMIC with on-chip antenna and silicon lens [26].

The functionality of the receiver was measured with the carrier frequency of 296 GHz and 3 different data rates (10, 20 and 27 Gbit/s). The eye diagrams showed (Fig. 11) that the package was applicable up to 27 Gbit/s rates.

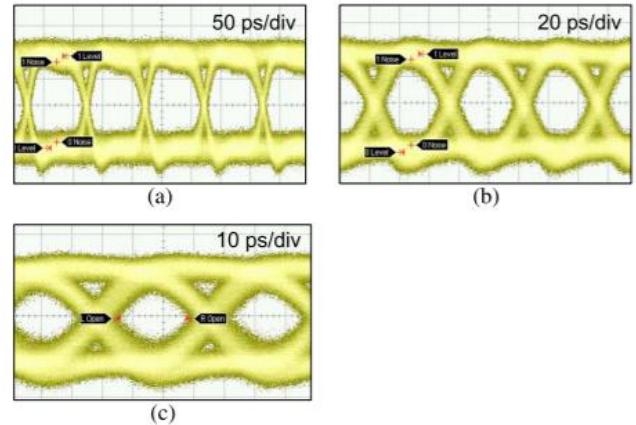


Fig.11. Measured eye diagrams at various data rates (10, 20 and 27 Gbps) at carrier frequency of 296 GHz [26].

IV. EXAMPLES FOR PHOTONICS

VTT has carried out a lot of the work for realization photonics applications with LTCC technology. An extensive reviews of the work are shown in [6,27].

The latest examples in this field are related to the packaging development for miniature atomic clocks [28,29]. The key element of the clock is so-called physics package. It provides all the interaction tools between the clock control electronics and the atoms. Fig. 12 shows a schematic of the physics package consisting of an evacuated, vacuum tight LTCC cavity that hosts a laser unit, two photodiodes (PD) and the atomic vapour cell. The optical coupling between the laser, photodiodes and cell was realized by a planar optical waveguide with grating couplers. The laser and the atomic cell (as well as one of the photodiodes) were mounted on an isostatic holder that ensured thermal isolation between the heated laser and the heated cell with respect to their surroundings. The LTCC package was sealed in vacuum although this part still requires further development.

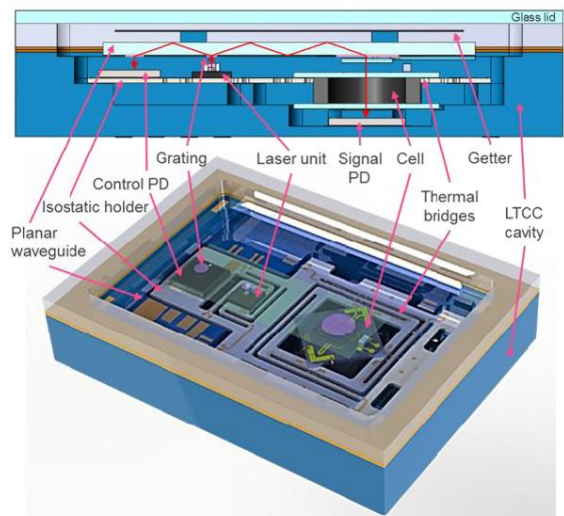


Fig.12. Overview of the physics package based on LTCC.

V. ASSEMBLY METHODS

The most common assembly method, wire-bonding, suffers from parasitic inductance. For example, a 1-mm long bond wire has a reactance of around $500\ \Omega$ at 80 GHz. At lower microwave frequencies, the bond wire inductance of SMT packaged ICs is tolerated by capacitive compensation. Careful optimisation of the parasitic shunt capacitance at each end of the wire bond allows its inductance to be absorbed into a low-pass filter (LPF) offering low insertion loss across the operating band. This same approach can be used at E-band but the maximum inductance that can be absorbed into the LPF is much lower. Therefore, it is essential to minimise the parasitic inductance. In practise, this means that the physical length of the bonding wire has to be reduced. Therefore, the bonding pads of the chip and substrate should be on the same level. This can be achieved with direct die-to-die bonding or by using bonding shelves in bonding from die to substrate. In addition, it would be useful to use 2 bonding wires next to each other in V-shape or use ribbon bonding. V-shape bonding means that the wires are not exactly parallel. In this way the mutual inductance can be reduced. This is an obvious choice when the die is wire-bonded to the transmission lines on the substrate where the lines tend to be wider. Ribbon wire has a larger cross-section than wire allowing a lower parasitic inductance for the same length [30].

Flip-chip process results in lower electrical losses in comparison with wire/ribbon-bonding processes. In the process, the semiconducting die or chip is electrically connected face down to a substrate. The bumps of different materials are realized onto area-array metallized terminals on the die. The die is then flip-chipped to matching footprints of pads on the chosen substrate. Different kinds of processes are available such as solder bonding, adhesive bonding and microwelding.

Although the flip-chip process is a good idea from the electrical point of view, there are some issues related to the thermo-mechanical performance. The differences in the coefficient of thermal expansion (CTE) of the die and substrates cause high stresses into the bumps. In the case of high-power component, the dissipation of heat has to be considered carefully. For example, alumina and some LTCC materials have a CTE of 7 ppm/K, which matches quite well with that of GaAs (6 ppm/K).

The use of underfill might be essential in some applications. It can re-distribute stresses caused by the mismatched CTE between dissimilar materials. It has been demonstrated that the underfill can reduce the solder strain level to 10-25% of the strain in joints which are not encapsulated. However, they might be quite lossy at millimetre waves. This is the case especially with commonly used epoxy-based underfills. Other materials, such as benzo-cyclobutene (BCB), are becoming available for mm-waves applications. It has been measured that dielectric loss of BCB is as low as 0.0008 @ 20 GHz meanwhile in the case of epoxies it can be as high as 0.02 @ 10 MHz [31].

CONCLUSIONS

This article focused on the utilization of the LTCC technology for millimeter-wave and photonics applications mainly from VTT's point of view. The key benefits of the technology are related to the stability and performance of materials and structures at frequencies up to 300 GHz. Three-dimensional structures, such as integrated embedded channels, enable the

realization of cooling structures needed for high-power lasers or amplifiers. 3D structures also allow the realization of sophisticated packages where the miniaturized atomic clock was shown as an example.

The main process for printing conductors is screen-printing. The process allows printing of $\sim 50\ \mu\text{m}$ wide lines. This has been adequate for 60-77 GHz applications. However, when moving to higher frequencies, other processes such as thin-film processing, might be required. Another approach is to replace the conductors with substrate-integrated waveguides where the signal propagates in the dielectric media covered by top and bottom metals and by vias as virtual walls. This kind of approach worked up to 300 GHz and was demonstrated by the lens receiver module.

In most cases only the fabrication of substrates is not sufficient. The assembly of components needs to be considered. Flip-chip process (such as bump size and height) and thermal management will become more and more important in the future due to the increased needs for enhancing integration density.

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